

11. Cryogenic Systems

11.1 Introduction

The proposed Neutrino Factory will require an extensive helium cryogenic installation to provide sufficient cooling for subsystems that are based on superconducting technology, e.g. the target solenoid, the solenoid channels, the various accelerating stages and the storage ring. The design of such a system is an iterative process of optimization of cost and performance with respect to the many requirements, both quantitative and qualitative. The starting point of the iteration is a system concept with point designs for the major processes. In the following paragraphs a first approximation to such a starting point is presented.

11.2 Refrigeration Plant and System Layout

An important feature of the cryogenic system of the Neutrino Source is the variety of components in the system, and the mixture of warm and cold components along the beam lines. It is inevitable in the Neutrino Factory that distribution of cryogens to a system of cryogenic modules is a major issue. It is reasonable to investigate a system that has one refrigeration plant first. A possible layout of this type is pictured in Figure 1. The refrigeration plant is centrally located, and five cryogen transfer lines distribute cooling to the cryogenic modules in five subsystems: one line serving the injector components and the pre-accelerator linac; one line for the linacs of RLA1; two lines (a loop) for the two linacs and the superconducting magnet systems of RLA2; and one line for the superconducting magnet systems of the storage ring. Figure 1 is schematic. The lengths of the lines given here are estimated from the site layout in chapter 13 on civil construction.

Figure 1: Layout of Transfer Lines

11.3 System Process

Refrigeration is provided by the plant in four forms. Table 1 lists the refrigeration plant streams and gives appropriate thermodynamic details.

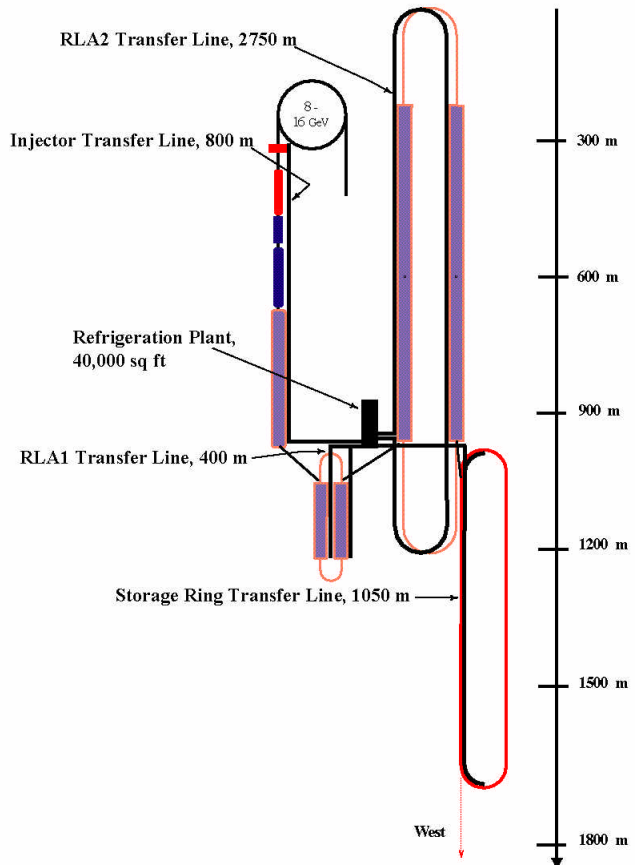
- 1) 4.5 K refrigeration is provided by a flow of helium at 3 bar pressure and 4.5 K. This is expanded in a J-T process (Joule Thomson) to saturated helium at 4.5 K. The saturated gas is returned to the refrigeration plant.
- 2) 4.5 K liquefaction is provided from the 3 bar, 4.5 K stream returning at 1 bar and 300 K.
- 3) Shield cooling is provided by a stream delivered from the refrigeration plant at 19 bar and 40 K and returned at 16 bar and 60 K.
- 4) 40 K liquefaction is provided from the 19 bar, 40 K stream also returning at the standard state.

11.4 Cryogenic System Components

At the level of abstraction of this report, the cryogenic system of the Neutrino Factory consists of three kinds of components: Refrigeration plant; transfer line; and boxes. These will be described below.

11.4.1 Refrigeration Plant

Anticipating the results of the capacity requirement roll up and from the discussion below, the capacity required in this plant for the Neutrino Factory is 80 kW equivalent at 4.5 K. This is equal to two LHC-size refrigeration stations. LHC is installing four stations each with two cold boxes of 20 kW equivalent capacity at 4.5 K [1]. This experience makes the specification and procurement of a refrigeration plant for the Neutrino Factory a straightforward engineering task with low risk.



The Neutrino Factory plant will contain approximately twenty helium screw compressors, oil removal, and inventory management equipment. This system will require about 24,000 square feet of medium rise floor space isolated for noise control and ventilated for about 2 MW of heat dissipation. The cold boxes will require about 15,000 square feet of space. In addition 1,500 square feet of air-conditioned space would be needed for control system electronics and local control room.

The total installed power in this plant will be about 25 MW with a nominal operating power of about 18 MW. Heat rejection of 25 MW with redundancy will be needed.

11.4.2 Transfer Line

The transfer line system includes four cold lines and two warm lines. The cold lines carry the supply and return streams listed in Table 1.

The sizes required for these lines will be different for the different transfer lines, but typical sizes are: 2 and 3.5 inch ips sch 5 for the 4.5 K supply and return; and 2.5 inch ips, sch 5 for the 40 - 60 K shield system supply and return. The transfer line will contain a shield thermally connected to the 60 K return line. The outside diameter of the vacuum jacket of the cold line assembly will approximately 18 inches.

Stream / Condition	Pressure	T	Enthalpy	Exergy	Ideal work	Watts/watt
	bar	K	J/g	J/g	J/g	
Standard State	1.0	300	1573.516	7910		
4.5 K Refrigeration - Carnot						65.667
4.5 K refrigeration - Supply	3.0	4.5	11.782	1075		71.825
4.5 K Refrigeration - Return	1.2	4.5	31.526	2493		
4.5 K Liquefaction					6835	
40-60 K Refrigeration Supply	19.0	40	223.611	4259		6.14
40-60 K Refrigeration Return	16.0	60	329.762	4911		
40 K Liquefaction					3651	

Table 1: Refrigeration Plant Streams and Thermodynamic Conditions

The two warm lines are warm helium gas supply and return - the supply for module purging and warm-up and the return for the liquefaction load and for module cool-down. The sizes of these lines might be 2 and 4 inch ips.

The transfer line system will include other components such as supports, periodic vacuum barriers in the cold line, and an insulating vacuum system with monitoring.

11.4.3 Boxes

The variety of requirements for modules that must operate in this cryogenic system can best be satisfied by providing a minimum set of components in each connection box. These components are needed for connecting an individual module to the transfer line. Each module will contain the special equipment required in addition to the minimum set. Examples of special situations are modules that have saturated helium baths or current leads. The saturated bath would need a liquid level gauge and the current leads would need flow control for the liquefaction flow.

In general the boxes will require four cold shut-off valves, two cold control valves, and valves for the warm gas lines. In addition there will be a vacuum barrier between the transfer line and the module and some means of disconnecting the module - U-tubes or field joints. Some instrumentation and some relief devices will be standard in the boxes as well.

11.5 Module and Component Heat Loads

Cryogenic system heat loads in each of the four categories for modules in the Neutrino Factory subsystems are given in Table 2 below with discussion following. These are divided into static and dynamic components. The static heat load is that which is present when the beam and all power supplies are not operating.

11.5.1 Current Leads

The Neutrino Factory is assumed to use HTC current leads throughout. The HTC bottom ends of the leads are to operate up to 60 K and are to be conduction cooled. The top ends are to be cooled by a flow of 40 K from the shield circuit returned to the refrigeration plant at 300 K. This is high-pressure gas regulated by a valve at room temperature,

and the circuit will probably have to have a cold shut-off valve. In the heat load estimate the requirement is taken to be 0.1 g/s at 40 K and 1 Watt at 4.5 K both per kA-pair. The 40 K liquefaction load is divided equally into static and dynamic.

11.5.2 Target Solenoid and Channels

Heat load estimates for the target solenoid were made at the National High Magnetic Field Laboratory [1][2]. The heat load estimates for the solenoid channels appear in chapter 9. It is assumed that each channel will have one pair of 6 kA current leads.

Module	Number	Boxes	Static Heat Load			Dynamic Heat Load		
			40 - 60 K	4.5 K	4.5 K Liq.	Lead kA	40 - 60 K	4.5 K
			Watts	Watts	g/s	kA	Watts	Watts
Injector								
Target Solenoid, 20 T	1	1	42	420		10		
Decay Channel	1	1	900	70		6		
LIA Channel	1	1	2000	260		6		
Cooling Channel	1	1	4600	400		6		
3.4 GeV Linac								
200 MHz short module	16	16	200	33	0.1			27.5
200 MHz long module	30	30	300	50	0.2			55
Focusing Solenoid	46	46	200	33		1		
RLA I								
200 MHz long module	24	24	300	50	0.2			55
RLA II								
400 MHz Long Modules	91	91	200	33	0.2			132
East Arcs								
Splitter Magnets	8	8	200	33		5		
Half-Arc	10	20	540	90		25		80
West Arcs								
Splitter Magnets	6	6	200	33		5		
Half-Arc	8	16	540	90		25		80
Storage Ring								
Half-Arcs	4	8	540	90		50	3717	441
Total Modules	247							
Total Boxes		269	50	20				
Total Transfer Lines, m	5000		2.5	0.1				

Table 2: Heat Loads of Modules and Components

11.5.3 Superconducting Linac Modules

The average heat load of the 10 m cryomodules of the 350 MHz LEP SRF system is 80 watts at 4.5 K. This system does not have intermediate temperature shielding, but it does have a 4.5 K liquefaction load of 0.25 to 0.05 g/s per cavity from gas cooling on HOM cables, beam tubes, tuners and power couplers [4][5]. The KEKB coupler also uses gas cooling [6], and in the design of SNS 0.05 g/s static and 0.025 g/s dynamic is allowed for each coupler[7]. The

cryomodules for both CEBAF and the TESLA TTF have heat loads of about 1 W/m average for the parts of the system at 4 K and below.

It is somewhat difficult to directly extrapolate values for the 200 MHz 10 m long modules from this disparate set of previous designs. However, it would probably safe but not extravagant to estimate 5 W/m for the 4.5 K refrigeration load for these modules. Also we can take the 80 W load mentioned above as the shield load for the long modules,

Subsystem	Number	Loads						
		Static				Dynamic		
		40 - 60 K	40 K Liq.	4.5 K	4.5 K Liq.	40 - 60 K	40 K Liq.	4.5 K
		Watts	g/s	Watts	g/s	Watts	g/s	Watts
Front End		8742	1.4	1298	0	0	1.4	0
Target Solenoid, 20 T	1	42	0.5	430	0	0	0.5	0
Decay Channel	1	900	0.3	76	0	0	0.3	0
Induction Linac Solenoid	1	2000	0.3	266	0	0	0.3	0
Cooling Channel	1	4600	0.3	406	0	0	0.3	0
Transfer Line, m	400	1000		40				
Boxes	4	200		80				
3.4 GeV preaccelerator		27000	2.3	5472	7.6	0	2.3	2090
200 MHz short module	16	3200	0	528	1.6	0	0	440
200 MHz long module	30	9000	0	1500	6	0	0	1650
Focusing Solenoid	46	9200	2.3	1564	0	0	2.3	0
Transfer Line, m	400	1000		40				
Boxes	92	4600		1840				
RLA I		9400	0	1720	4.8	0	0	1320
200 MHz long module	24	7200	0	1200	4.8	0	0	1320
Transfer Line	400	1000		40				
Boxes	24	1200		480				
RLA II		44645	26	8700	18.2	0	26	13452
400 MHz Long Modules	91	18200	0	3003	18.2	0	0	12012
<i>East Arcs</i>								
Splitter Magnets	8	1600	2	304	0	0	2	0
Half-Arc	10	5400	12.5	1150	0	0	12.5	800
<i>West Arcs</i>								
Splitter Magnets	6	1200	1.5	228	0	0	1.5	0
Half-Arc	8	4320	10	920	0	0	10	640
Transfer Line, m	2750	6875		275				
Boxes	141	7050		2820				
Storage Ring		5185	10	825	0	14868	10	1764
Half-Arcs	4	2160	10	560	0	14868	10	1764
Transfer Line, m	1050	2625		105				
Boxes	8	400		160				
Total Load by Category		94972	39.7	18015	30.6	14868	39.7	18626

Table 3: Cryogenic Load by Subsystem and Category

applying one factor of two for the larger size and a second factor of two rounded down to reflect the fact that we will not want the shield to be a critical item. Including 0.05 g/s of 4.5 K liquefaction for each cavity, the total static cryogenic load of the 200 MHz 10 m module is estimated to be 50 Watts at 4.5 K, 300 Watts at 40-60 K and 0.2 g/s liquefaction at 4.5 K.

To get a similar estimate for the static loads 200 MHz short module and the 400 MHz module we take 2/3 of the load for the 200 MHz long module. The dynamic loads of the linacs are discussed in Chapter 7 of this Report. The values taken in Table 2 are the baseline values chosen in the Superconducting Study Meeting [11][12]: these are for the Preaccelerator, 2090 W; for RLA1, 1337 W; and for RLA2, 12,034 W. This is approximately a factor of three more than what has been presented in chapter 7, which assumed an ideal case with all the cavities achieving the specified Q0 and no contributions to the dynamic load from other sources (field emission, higher order modes, couplers etc). The number presented here is certainly conservative in that sense and should become smaller as the R&D progresses.

11.5.4 Half-Arcs of the Storage Ring

The arcs of superconducting magnets in the muon storage ring are illustrated and discussed in Chapter 8 of this report. Each of the two arcs is divided into two half-arc cryogenic modules each about 86 m in length. For the purposes of estimation of the cryogenic performance, each of the half-arcs contains 9 cells: a total of 18 dipoles and 18 quadrupoles; and each operates as a magnet string with a feed box at one end and an end box at the other. The magnet string operates with a flow of 40 g/s of single-phase helium, which passes down the length of the string in alternating half-cells and recoilers, and returns down the string again in alternating half-cells and recoilers. After passing through all of the magnets in the string, the single phase flow is flashed into the shell side of the recoilers. The two-phase sides of the recoilers are connected in series.

The heat loads are estimated in Chapter 8: the static load is 5 W per half-cell at 4.5 K and 30 W at 40-60 K. The dynamic loads are due to particle heating of the magnet iron and of the tungsten liner inside the magnet bore which is cooled by a flow of 40-60 K helium. The total lead current is 50 kA for each arc of the storage ring. It has been assumed that the half-arcs will have a transfer line connection box at both ends.

Issues in the storage ring cryogenic system are first, the large tilt of the ring, and second, the deep location of the west arc of the ring. The tilt requires that the magnet strings of the arcs operate on a slope that varies from about 20 % at the end of the arc to level at the apex of the ring. This presents problems in controlling the flow of the two-phase helium in the recoilers mentioned above. Each of the 4 strings of magnets will have to be operated so that the two-phase flow is down hill, and the recoilers will have to be equipped with wiers to distribute the two-phase fluid on the heat exchange surfaces. CERN has had to take similar measures in the LHC which has a slope much smaller than here. The 200 meter depth of the west arc in the storage ring presents problems with head pressure in the distribution of cryogens. For example, a 200 m head of saturated liquid helium is a pressure of 2.3 bar and of saturated gas, 0.43 bar. These are significant pressures compared to the saturation pressure of 1.3 bar, at it is clear that the depth places requirements on the cryogenic system. At LHC this problem is dealt with by dividing the refrigeration plant cold boxes at the 20 K level, putting the cold end down in the tunnel. This would be appropriate for the storage ring if it proves to be cost effective to have a local plant rather than distributed refrigeration for the deep end. An alternative to this is to put a cold compressor at the deep end to provide the head pressure. This was the choice made in the SSC cryogenic system design and it will work here also.

11.5.5 Solenoids of the Pre-Accelerator and Splitters and Arcs of RLA2

At the time of the Superconducting Study Meeting [11][12] there was no engineering design for the magnetic elements in the Pre-accelerator or the arcs of RLA2. For the purposes of cryogenic load estimation we take the static loads in the arcs of RLA2 to be the same as those in the arcs of the storage ring. The dynamic load due to particle loss in the last arc of RLA2 is estimated to be 2 W/m [12]. We therefore choose half this peak value or 80 W per half-arc for the dynamic load. Likewise we use half of the magnet current of the storage ring for an average in the RLA2 arc.

Proceeding in the same way to choose static and loads for the pre accelerator solenoids and the splitters in RLA2 we take the same values as for the short 200 MHz module, recognizing that this may, at least in the case of the solenoids, be an over-estimate.

11.5.6 Transfer Lines and Boxes

The heat load of the transfer lines are taken to be roughly the same as the LHC Cryogenic Distribution Line [1]. This includes functions of both the Neutrino Factory transfer lines and boxes and does not include shut-off valves for all circuits or disconnect devices such as u-tubes. The heat load values for the lines and boxes in Table 2 includes allowances for the valves, and for module connection piping.

11.6 Cryogenic Load of the Neutrino Factory Subsystems

In Table 3 the component and module heat loads are added up and displayed by category for each of the five cryogenic subsystems. The transfer line lengths and boxes have been distributed among the subsystems, so that the table gives the connected load for each subsystem.

11.7 4.5 K Equivalent Cryogenic Loads

In order to get a feeling for what is implied in terms of hardware by the cryogenic loads presented in Table 1, and to be able compare and combine loads in different categories to get an estimate of total refrigeration plant requirement, it is convenient to reduce all of the loads to a common basis in thermodynamic ideal power. The ideal power is familiar as the power required to reversibly move heat from a temperature T to a higher temperature T_o . According to Carnot's formula this is $(T_o - T)/T$. For refrigeration at 4.5 K with heat rejection at $T_o = 300$ K the ideal work is 65.7 Ideal watts per watt of refrigeration. This is given also in the second line of Table 1 above. Ideal work or power can be determined for all of the categories of refrigeration plant load, and these are given in Table 1 also. For example, refrigeration with a supply and return at 4.5 K as indicated in lines 3 and 4 of the table requires 71.8 w/w and refrigeration at 40-60 requires 6.14 w/w. The ideal power of a refrigeration process is given in terms of J/g, that is ideal power per g/s of flow.

The ideal power equivalents in Table 1 are used to express the loads in Table 3 in terms of equivalent power at 4.5 K. These are given in Table 4 below together with the percentage distribution of the equivalent power over the five cryogenic subsystems.

This table presents the start of a second law analysis of the Neutrino Factory cryogenic system. It is interesting to note that 70% of the equivalent load is in the static and dynamic loads at 4.5 K., about 20% in the shielding loads; and only 10% in liquefaction. This suggests that as the engineering design of the components gets started, trying to intercept more heat on the shields and in liquefaction streams could reduce the operating cost and the size of the cryogenic plant

The total equivalent load is approximately 60 kW. This gives an understanding of both the size and cost of cryogenic plant for the Neutrino Factory. The CERN cryogenics group gives scaling methods [2][3] by which plant equipment cost can be scaled from equivalent load. Also we can say that the equivalent load here requires a plant capacity approximately half that of LHC for high-availability operation.

	Equiv. Load	Percent	Percent by System				
	Watts at 4.5 K		Injector	Linac	RLA1	RLA2	Ring
Static			8	16	23	28	39
40 - 60 K	8880	15.3	1.41	4.36	1.52	7.20	0.84
40 K Liq.	2207	3.8	0.13	0.22	0.00	2.49	0.96
4.5 K	19704	34.0	2.45	10.33	3.25	16.42	1.56
4.5 K Liq.	3185	5.5	0.00	1.37	0.86	3.27	0.00
Total Static	33977	58.6	3.99	16.27	5.63	29.39	3.35
Dynamic							
40 - 60 K	1390	2.4	0.00	0.00	0.00	0.00	2.40
40 K Liq.	2207	3.8	0.13	0.22	0.00	2.49	0.96
4.5 K	20373	35.2	0.00	3.94	2.49	25.39	3.33
Total Dynamic	23970	41.4	0.13	4.17	2.49	27.89	6.69
Total Load	57947	100.0	4.13	20.44	8.12	57.28	10.04

Table 4: Load Equivalent at 4.5 K

REFERENCES

- [1] *The Large Hadron Collider - Conceptual Design*, (The Yellow Book) CERN/AC/95-05(LHC) October 1995
- [1] Private communication from Mr. Soren Prestmon, NHMFL S. Claudet,
- [2] S. Claudet, Ph. Gayet, Ph. LeBrun, L. Tavian, and U. Wagner, "Economics of Large Helium Cryogenic Systems: Experience from Recent Projects at CERN", *Advances in Cryogenic Engineering*, **V45**, Plenum Press, New York 2000 (also CERN LHC Project Report 317, Dec., 1999)
- [3] L. Tavian and U. Wagner, "LHC Sector Heat Loads and Their Conversion to Refrigerator Capacities", CERN LHC Project Report 140, May, 1998
- [4] G. Cavallari et. al., "Status Report on Sc.RF Cavities at CERN" in *Proceedings of the 5th Workshop on RF Superconductivity*, D. Proch, Editor, DESY August 19 - 23, 1991, DESY M-92-01, April 1992
- [5] G. Cavallari et. al., "Status of the RF Superconductivity at CERN" in *Proceedings of the 6th Workshop on RF Superconductivity*, R. Sundelin, Editor, CEBAF October 4 - 8, 1993
- [6] S. Mitsunobu et. al., "High Power Test of the Input Coupler for KEKB SC Cavity" in *Proceedings of the 7th Workshop on RF Superconductivity*, B. Bonin, Editor, Gif-Sur-Yvette, France, 1995, p735-739 CEA/Saclay/96 080/1
- [7] Superconducting Radio Frequency Linac for the Spallation Neutron Source, Preliminary Design Report SNS-SRF-99-101 December 1999
- [8] W. Schneider et. al., "Thermal Performance of the CEBAF Superconducting Linac Cryomodule", *Advances in Cryogenic Engineering*, **V39**, p589-596 Plenum Press, New York 1993
- [9] F. Alessandria et. al., "Design, Manufacture and Test of the TESLA-TTF Cavity Cryostat", *Advances in Cryogenic Engineering*, **V41**, p855-861 Plenum Press, New York 1995
- [10] G. Horlitz, T. Peterson, and D. Trines "The TESLA 500 Cryogenic System Layout", *Advances in Cryogenic Engineering*, **V41**, p911-920 Plenum Press, New York 1995
- [11] Superconducting RF Study Meeting, Held at Fermilab February 17 - 18, 2000. Draft Summary by N.Holtkamp issued March 1, 2000.
- [12] Private communication from M. Harrison, BNL